Use of Thermoregulatory Models to Enhance Space Shuttle and Space Station Operations and Review of Human Thermoregulatory Control

by

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ABSTRACT
Thermoregulation in the space environment is critical for survival, especially in off-nominal operations. In such cases, mathematical models of thermoregulation are frequently employed to evaluate safety-of-flight issues in various human mission scenarious. In this study, the 225-node Wissler model and the 41-Node Metabolic Man model are employed to evaluate the effects of such a scenario. Metabolic loads on astronauts wearing the advanced crew escape suit (ACES) and liquid cooled ventilation garment (LCVG) are imposed on astronauts exposed to elevated cabin temperatures resulting from a systems failure. The study indicates that the performance of the ACES/LCVG cooling system is marginal. Increases in workload and or cabin temperature above nominal will increase rectal temperature, stored heat load, heart rate, and sweating, which could lead to deficits in the performance of cognitive and motor tasks. This is of concern as the ACES/LCVG is employed during Shuttle decent when the likelihood of a safe landing may be compromised. The study indicates that the most effective mitigation strategy would be to decrease the LCVG inlet temperature.

INTRODUCTION

The advanced crew escape suit (ACES) and liquid cooled ventilation garment (LCVG) provide pressure, oxygen concentration and temperature regulation to astronaut crewmembers in the extreme environment employed during launch and entry operations of the Space Shuttle. For humans to function normally in such a hostile setting, it is necessary to emulate a terrestrial “Earth-like” setting. The ACES/LCVG ensemble does this by first maintaining a non-toxic atmosphere with a partial pressure of oxygen between 120 to 280 mmHg. This brackets the sea level partial pressure of oxygen of 160 mmHg on Earth. (Hypoxia occurs below a partial pressure of 120 mmHg and hyperoxia at a partial pressure greater than 280 mmHg of oxygen.) Secondly, the ACES/LCVG system insures that astronauts do not undergo a rapid reduction in pressure or G level, which could cause decompression sickness (DCS) or blackouts. Thirdly, and the focus of this paper, the ACES/LCVG ensemble must maintain an acceptable thermal environment for the crew as they carry out their activities, including launch./entry operations that could occur in potentially extreme external environments under significant metabolic loading.

This study focused on the effect of elevated Shuttle cabin temperatures and workloads on astronauts during reentry while wearing the ACES and LCVG. The study was prompted due to the failure of a flash evaporator controller in the Shuttle Active Thermal Control System (ATCS) during the STS–111 Endeavour mission. If the backup controllers had also failed, the crew would have been exposed to increased cabin temperatures that could have resulted in significant performance decrements during the most critical entry/landing phase of the mission.

To investigate the effect of such a failure, two mathematical models of human thermoregulation were employed, the 225-node Wissler model and the 41-Node Metabolic Man model. These models have a rich legacy of mission support, dating back to the Apollo Program when the 41 Node Metabolic Man model was used for real-time management of Extravehicular Mobility Unit (EMU) consumables, astronaut safety, and EVA traverse objectives on the Lunar Surface (8), (15). For this study, both the 41 Node Metabolic Man model (6), (7) and the Wissler model were modified and adapted for a personal computer (16), (17), (18). After correlating them with data from related extreme environment studies, they were then used to evaluate the ACES/LCVG system and propose solutions to the marginal performance characteristics that were predicted.

HUMAN THERMAL REGULATION

Humans are classified as a *homeotherms*, organisms that have nearly constant body temperature that is largely independent of the temperature of their surroundings. Human oral core body temperature is 37 ^{o}C with a diurnal variation of only about 0.5–0.8 ^{o}C. Lower values occur in the early morning and higher values in the late afternoon. Rectal core temperatures are slightly higher than oral core temperatures with an average of 37.5 °C and exhibit similar diurnal variation. Exertion that increases the metabolic rate increases core temperature. Major factors affecting human thermal regulation in a gaseous environment are shown in Table 1.

Environment	Physiology	Clothing	Operations
1. Temperature 2. Humidity 3. Air Movement 4. Radiant Exchange 5. Barometric Pressure 6. Gas Composition	1. Circadian Rhythm 2. Metabolic Rate (absolute) 3. Metabolic Rate (percent capacity) 4. External Work 5. Hydration 6. Acclimation/ Acclimatization 7. Body Temperature (skin and core) 8. Ventilation Rate 9. Sweat Rate 10. Skin Wetness	1. Insulation 2. Vapor Permeability 3. Wind Permeability	1. Time of Day 2. Duration 3. Sequence of conditions 4. Recovery Intervals 5. Artificial Cooling 6. Other Stresses a. Acceleration b. Toxins c. Psychology (anxiety and accustomization)

Table 1 Major Factors Affecting Human Thermal Regulation in a Gaseous Environment, from (14)

Thermoregulation is the process by which the body maintains its nominal core temperature given changes in external temperature and metabolic loading. Increases or decreases in metabolic rate respectively increases or decreases the production of heat. Factors that affect the metabolic rate include exercise, hormone levels, stress, ingestion of food, age, and gender. Heat is transferred from or to the surface of the body and lungs by radiation, evaporation, conduction, and convection. Thus, the balance between heat production and loss is derived from the first law of thermodynamics

$$\dot{Q}_m = \dot{Q}_e + \dot{Q}_r + \dot{Q}_k + \dot{Q}_c + \dot{Q}_{st} + W \tag{1}$$

where

$\dot{Q}_m$ = metabolic heat rate

$\dot{Q}_e$ = evaporative heat loss positive, gain negative

$\dot{Q}_r$ = radiative heat loss positive, gain negative

$\dot{Q}_k$ = conductive heat loss positive, gain negative

$\dot{Q}_c$ = convective heat loss positive, gain negative

$\dot{Q}_{st}$ = heat storage rate

W = mechanical work

Body temperature is controlled by negative feedback that requires sensors, a controller, and actuators. In addition to the hypothalamus itself that also acts as a sensor, cold and warm sensitive temperature receptors are located throughout the body. The body temperature receptors are located in the skin and in the interior of the body, specifically in the spinal cord, abdomen, larger veins, and thorax. The hypothalamus, primarily neurons in the anterior hypothalamic-preoptic region, is generally recognized as the body's temperature controller or thermostat. The hypothalamic thermostat works in conjunction with other hypothalamic, autonomic, and higher nervous thermoregulatory centers to keep core body temperature constant. Temperature sensitive neurons in the hypothalamus are stimulated by the temperature receptors. Warm sensitive neurons in the hypothalamus increase their firing rate in response to an increase in body temperature to promote heat loss. Cold sensitive neurons in the hypothalamus increase their firing rate in response to a decrease in body temperature to promote heat conservation and increase

heat production. Additional thermoregulatory responses are involuntary, mediated by the autonomic nervous system, some neurohormonal, and others semi-voluntary or voluntary behavioral responses.

If the core body temperature decreases below the set point, cold sensitive neurons, primarily in the anterior hypothalamic-preoptic region, initiate the following hyperthermic responses:

Cutaneous Vasoconstriction – Stimulation from the posterior hypothalamic-preoptic sympathetic centers constricts smooth muscles in the arterioles near the body's surface. As a result, warm blood is moved deeper within the body so that heat loss is reduced. Maximal vasoconstriction can decrease cutaneous blood flow to 30 mL min^{-1} from a nominal flow of 300-500 mL min^{-1}.

Piloerection – Piloerection as a response to cold is vestigal in humans. Since humans retain only very little body hair, the reflex does not serve a useful purpose. The sympathetic nervous system causes small muscles at the base of each hair, the arrectores pilorum, to contract and pull the hair erect resulting in goose bumps in humans. While not important for humans, piloerection in animals allow the entrapment of a thicker layer of insulated air to reduce heat transfer.

Chemical Thermogenesis – Production of Thyrotropin Releasing Hormone stimulates the anterior pituitary gland to increase secretion of Thyroid Stimulating Hormone that in turn promotes production of Thyroxin (T4) by the thyroid that increases cellular metabolism that produces heat. In addition, an increase in sympathetic stimulation and release of epinephrine and norepinephrine from the adrenal medulla also increases cellular metabolism.

Shivering – The primary shivering motor center, located in the dorsomedial region of the posterior hypothalamus, is stimulated by signals from the cold sensitive receptors in the skin and spinal cord. When activated, the shivering motor center transmits signals to the anterior motor neurons that increase the tone of the skeletal muscles. When the tone increases above a critical level, shivering is initiated. Shivering can increase surface heat production by 500%. However, this effect is limited to a few hours because of depletion of muscle glucose and the onset of fatigue.

If the core body temperature increases above the set point, the warm sensitive neurons, primarily in the anterior hypothalamic-preoptic region, initiate the following hypothalamic responses:

Skin Vasodilation – Inhibition of the adrenergic activity of the sympathetic centers in the posterior hypothalamus causes the smooth muscles of the arterioles to relax resulting in dilation of blood vessels in the skin. This increases skin blood flow and therefore temperature, promoting heat transfer out of the body. Maximal vasodilation can increase cutaneous blood flow to 3000 mL min^{-1} from a nominal flow of 300-500 mL min^{-1}.

Decrease in Metabolic Rate – Reduction in the metabolic rate decreases the production of heat by the body. This is realized by inhibiting the mechanisms that produce heat by chemical thermogenesis and shivering as discussed above.

Sweating – If the heat is sufficiently high, the cholinergic sympathetic fibers that innervate the sweat glands release Acetylcholine that stimulates sweat. This activation of the sweat glands produces sweat that results in heat loss through evaporation. By this mechanism, many times the basal metabolic heat rate can be removed.

A schematic of the thermoregulatory system is illustrated in Figure 1.

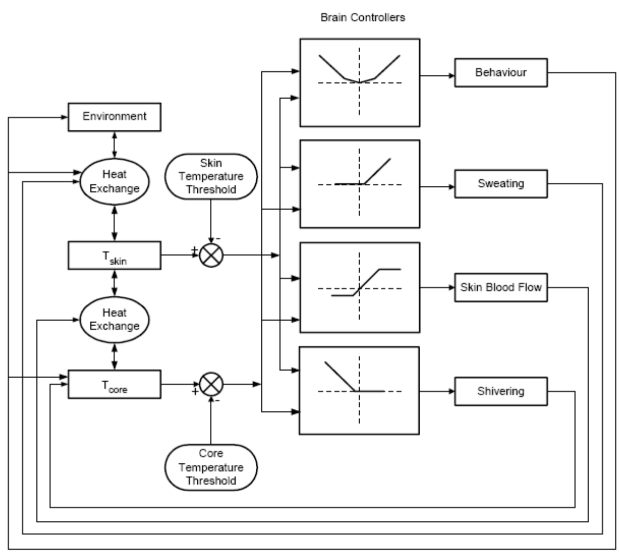

Figure 1 Thermoregulation Feedback Control, from (5)

The body's ability to maintain core and skin temperature in changing environments is critical to survival. However, if the external and or metabolic factors are extreme, the body cannot compensate and significant deficits will occur as identified in Table 2.

CONDITION	TEMPERATURES °C	SYMPTOMS
Heat Stroke	>44	Brain death certain
	41-44	Includes all systems of heat exhaustion plus disfunction of central nervous system causing altered mental state, disorientation, strong rapid pulse, coma, and beginning of brain death
Heat Exhaustion	39-41	Fatigue and weakness, nausea and vomiting, headache, muscle cramps, irritability, pulse raised
Heat Cramps	39–38	Painful muscle spasms with pulse normal or slightly elevated, often caused by salt depletion
Normal	38–36	Normal
Mild Hypothermia	36–35	Cold sensation, goose bumps, lack of some hand coordination, shiver can be mild to severe
Moderate Hypothermia	35–34	Intense shivering, apparent lack of muscle coordination, movements labored, mild confusion but appears alert
	34–32	Violent shivering, difficulty speaking, lack of some cognitive functions, muscle stiffness, sign of depression
Severe Hypothermia	32–30	Shivering stops, incoherence, poor muscle coordination, irrational and confused, inability to walk,
	30–28	Muscle rigidity, semiconsciousness, pulse and respiration decrease, pupil dilation, desire to sleep, possible heart fibrillation
	28–26	Unconscious, muscle failure, pulse and heart rate erratic, respiratory failure, possible death
	< 26	Pulmonary edema, cardiac and respiratory failure, death

Table 2 Core Temperatures Effects

Both hypothermia and hyperthermia result in the impairment of normal cerebral and motor functions. The comfortability of a range of mean skin temperatures is given in Table 3.

Local Skin Temperature °C	**Degree of Comfort**
> 36	Uncomfortable
34-36	Slightly uncomfortable
34-32	Comfortable
32-30	Slightly uncomfortable
< 30	Uncomfortable

Table 3 Skin Temperature Comfortability

Other studies have similarly reported that small increases in body core temperature can impair the ability to carry out complex tasks. Increases in body temperature will adversely affect short-term memory and slow perceptual and motor skills. If the temperature increases to 38.3°C (101° F), for example, an aviator's error rate will roughly double (2). Table 4 identifies physiological levels of concern for individuals during military operations characterized by decrements in physical, cognitive, motor tasks, and potential damage resulting from (a) increased rectal temperature with elevated skin temperatures, (b) heat storage, and (c) heart rate (3).

Rectal Temperature With Elevated Skin Temperatures		
Physical Tasks		
	38.2°C	NIOSH limit of discomfort
	39.2°C	25 % risk of heat casualties
	39.5°C	50% risk of heat casualties
	40.0°C	100% risk of heat casualties
Cognitive Tasks		
	37.7°C	Threshold of decrement
	38.2°C	Slowed cognitive function
	38.5°C	Increased errors in judgment
	39.6°C	Suggested functional limit
Motor Tasks		
	37.9°C	Decreasing manual dexterity
	38.8°C	Loss of tracking skills
Heat Storage		
	Level	**Effect**
	80 kcal	Discomfort
	120 kcal	Performance degrades (rectal temperature ~ 39°C)
	> 200 kcal	Potential damage
Heart Rate		
	Level	**Effect**
	120 bpm	Discomfort, 8-hour tolerance
	140 bpm	4-hour limit
	160 bpm	2-hour limit
	> 170 bpm	Potential damage, age related

Table 4 Physiological Levels of Concern, from (3)

DESCRIPTION OF ACES

The advanced crew escape suit (ACES) replaced the Launch/Entry Suit (LES) in 1995. It is designed to protect the Shuttle crew in the event of loss of cabin pressure up to an altitude of 30 km and to insulate the crew from cold air and cold water if they need to bail out in an emergency. During reentry, Shuttle astronauts also wear, under the ACES, anti-gravity pressure bladders in the legs and abdomen to resist pooling of blood in the lower body. The reduction of serum volume in microgravity can lead to reduced cognitive and motor functions due to a lack of cerebral perfusion during reentry. Since the ACES is waterproof, a liquid cooled undergarment is used to remove heat to maintain normal core body temperature. The thermal pathways for the astronaut in the ACES are illustrated in Figure 2, where the atmosphere in the ACES is the private atmosphere.

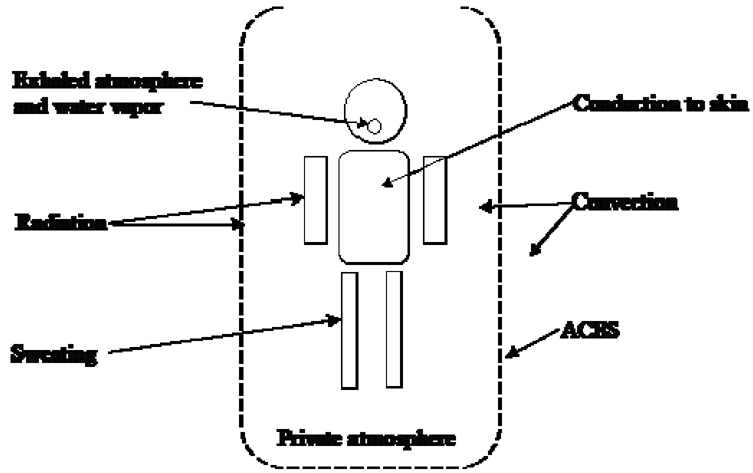

Figure 2 ACES Thermal Pathways

EFFECTS OF ELEVATED TEMPERATURE WITH THE ACES

Figure 3 illustrates the comfort zone for test subjects wearing the LCVG and ACES derived from tests in which the subjects performed various tasks at different workloads and environments (7). The comfort zone is determined primarily by skin temperature. The upper, or warm, limit corresponds to the threshold at which the subjects began to feel uncomfortable because of the inability of the LCVG to remove excess heat due to an elevated inlet coolant temperature. The lower, or cool, limit corresponds to the threshold at which the subjects began to feel uncomfortable because of the removal of heat by the LCVG with a low inlet coolant temperature. This comfort band is frequently used by NASA as a safety envelope for various tasks in extreme temperature environments such as for the ACES/LCVG suited subjects. It shows that a deviation in stored heat from comfort of ±16 kcal (±62 BTU) crosses the hot and cold thresholds at a nominal metabolic rate of 300 BTU h^{-1}.

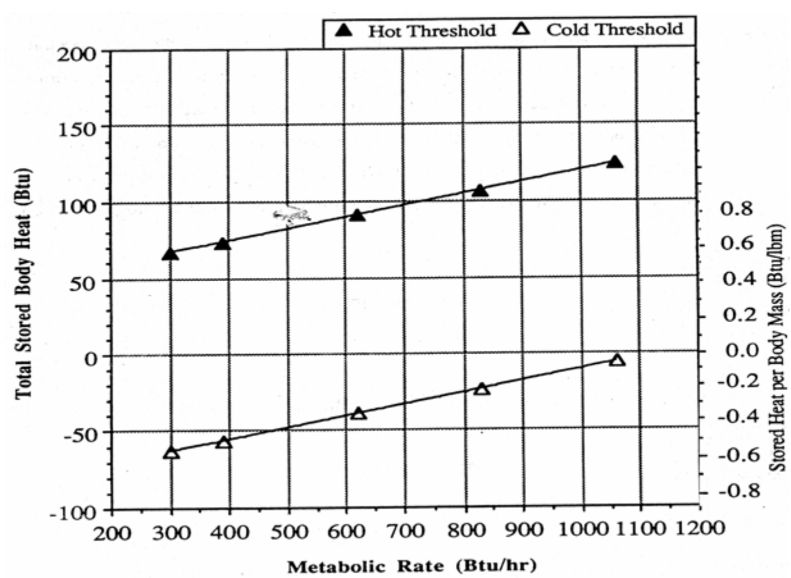

Figure 3 Comfort Zone for ACES Suited Subjects, from (7)

MATHEMATICAL MODELS OF THERMOREGULATION

Human body thermoregulatory simulators are generally modeled as a controlled or passive system being regulated by a controlling or active system. The passive system consists of multiple layers of tissue representing the core, muscle, fat and skin, while the active system simulates functional differences in the body's neural control system. In the passive system, skin layers exchange heat with the environment by conduction, convection, evaporation and radiation, while in the active system, signals proportional to temperature deviations from "set points" in the skin and hypothalamus are sensed by a detector (the neural system), modified by an integrator (the brain), and used as commands by effectors (the sweat glands, muscles and cardiovascular system). In this approach, commands such as sweating, shivering, and blood flow regulation are used to keep the body temperature constant and maintain homeostasis.

Because of the complexity of the human thermoregulatory system, large number of components should be taken into account in modeling. These include:

- environment
  constituents, pressure, temperature, humidity, and flow rate
- clothing
  thermal conductivity and permeability
- anatomical characteristics
  surface area, mass, body composition, heat capacity, gender, and age
- activity
  workload, metabolism, oxygen uptake, respiratory heat loss, and acclimation
- physiological response
  shivering, sweating, vasoconstriction, vasodilation, blood flow rate, and heart rate

The thermoregulatory models used here, the Wissler model and the 41 Node Metabolic Man were developed respectively by Eugene H. Wissler (16), (17), (18) and Lawrence H. Kuznetz (6). These models were modified to simulate an automatic control system for a liquid cooling garment to provide thermal comfort to astronauts and cover a broad range of human experiences from immersion in cold water to exercise in a hot humid environment (7), (8), (9), (12), (13), (19). The Wissler model utilizes a 15-element representation of the human body with 15 nodes in each element, for a total of 225 nodes and has been validated with the performance of divers working as deep as 450 meters and with subjects up to altitudes of 9000 m. The 41 Node Metabolic Man model has 10 elements with 4 nodes in each for a total of 41 nodes and has been validated for astronauts in thermal chambers wearing spacesuits in extreme environments. Each model uses concentric cylinders to simulate muscle, fat, bone, and skin and has a vascular system composed of arteries, veins, and capillaries. Physical properties and physiological variables (such as temperature, metabolic and perfusion rates, oxygen and carbon dioxide tensions, and lactate concentrations) are described as functions of polar coordinates and time. Algorithms are used to represent the thermoregulatory and cardiovascular responses. The heat transfer equations and material balances for oxygen, carbon dioxide, and lactate are evaluated by finite–difference methods.

SHUTTLE THERMAL CONTROL SYSTEMS

Thermal control in the Shuttle is provided by the Water Coolant Loop System (WCLS) that removes heat from a variety of air and water heat exchangers and returns cold air or water as appropriate. Radiators in the payload bay doors have the primary responsibility to reject heat while the Shuttle is in orbit with the bay doors open. Otherwise, during ascent and decent, when the bay doors are closed, a flash evaporator system is utilized. This system removes heat by spraying water on a coil and venting the resulting vapor overboard. During reentry below an altitude of 30.5 km (100,000 ft) the flash evaporator system can no longer provide sufficient cooling and heat rejection is then augmented by an ammonia boiler system until after landing, when ground support personnel attach the ground support heat exchanger. The cooling water in the LCVG of each astronaut exchanges heat with the cabin atmosphere by means of the thermal electric individual cooling units (ICU), which are under individual astronaut control. Consequently, if the cabin temperature is elevated, the inlet temperature of the cooling water in the LCVG will be elevated.

The STS-111 mission had the responsibility to return experimental test equipment from the International Space Station (ISS) that required continuous power. This produced an increased thermal heat load during reentry. Two days into the flight, Endeavour’s flash evaporator system primary B controller failed. Fortunately, the system’s back-up controllers continued to function normally so there was no effect on mission operations. It did, however, prompt consideration of corrective actions to be taken if both controllers had degraded. Such failures would have resulted in elevated cabin temperatures, which would have reduced the effectiveness of the LCVG. Such a decrement, and the concurrent effect on astronaut performance associated with it, would have occurred in the most critical phase of reentry.

MODEL VALIDATION

To assure that the human body thermoregulatory simulations were functioning properly, a series of verification checks was made. These included quantitative comparison with the results of simulations from prior implementations that compared to rounding errors, checked the conversion of selected inputs with internally computed parameters to assure that the inputs were being properly interpreted, and qualitative assessed the output to changes in the inputs. Two other validation tests were also carried out with data obtained from human subjects. The first validation utilized data obtained at the Naval Medical Research and Development Command provided by Hagan (4). This data set was of fully outfitted fire fighters whose rectal and mean skin temperature were recorded during exercise in moderate, warm, and hot air environments at high metabolic rates. Good agreement was obtained between the simulations and the measured core and mean skin temperatures. The second validation compared predictions with the results of a human subject test aimed at determining if the ACES and the LCVG could protect against a simulated Shuttle re-entry temperature profile higher than currently allowed by NASA flight rules (10). Eight subjects (4 males and 4 females) wearing the ACES and the LCVG were placed for 5 hours in a chamber in which the temperature, humidity, inlet water coolant temperature were increased and the water flow rate was under control of

the subjects. Good agreement was obtained for rectal temperature, mean skin temperature, and water outlet temperature. Both of these validations will be reported on in detail in another manuscript (in press).

SHUTTLE PARAMETRIC STUDY

The Wissler and 41 Node Man models were modified and configured to carry out a parametric study of astronauts clothed in the LCVG/ACES ensemble under the conditions of a degraded ATCS such as occurred on Endeavour. The simulated astronaut had the following properties:

Subject
- Mass = 72.7 kg (160 lbs)
- Mean Skinfold Thickness = 10 mm
- Position = seated
- Metabolic Rate
- Resting = 113.4 kcal h^{-1} (450 BTU h^{-1})
- Incremental component = varied from 37.8 kcal h^{-1} (150 BTU h^{-1}) to 630.0 kcal h^{-1} (2500 BTU h^{-1})
- 15% is assigned each to the muscles in the legs and arms and
- 35% each to the muscles in the lower and upper trunks

Environmental Conditions
- Pressure = 1 atmosphere
- Dry-bulb Temperature = is varied
- Black Globe Temperature = dry-bulb temperature
- Dew-point temperature = is varied so relative humidity is 50 percent
- Breathing = air at cabin temperature

LCVG
- Coolant flow rate = 36.4 kg h^{-1} (80 pounds h^{-1}) (maximum possible)
- Coolant inlet temperature = cabin dry-bulb temperature –2^{o}C

Figures 4 and 5 are the Wissler model's predictions of rectal and mean skin temperature versus time for a constant metabolic rate of 151.2 kcal h^{-1} (600 BTU h^{-1}) as cabin temperatures increase. Figure 6, by contrast, expresses steady state predictions of rectal temperature as a function of metabolic rate as cabin temperatures increase. The range of 300 to 400 kcal h^{-1} (1200-1600 BTU h^{-1}) in Figure 6 encompasses the upper limit of sustained metabolic rate for a fighter pilot at 300 kcal h^{-1} (1200 BTU h^{-1}) (1), and for an EVA at 400 kcal h^{-1} (1600 BTU h^{-1}). Based on Figure 6, relatively high metabolic rates such as these are sustainable only as long as cabin temperatures are kept below 20 degrees C. If, on the other hand, increases in cabin temperature caused by the type of failure analyzed in this study exceed this boundary, severe compromises in crew judgment, motor skills and landing/entry performance can result. This is expressed graphically in Figure 6, which tracks the rise in core temperature against CDO (Cognitive Deficit Onset), DMD (Decreasing Manual Dexterity) and Loss of Tracking Skills (LOTS) redlines. The CDO, DMD and LOTS redlines were determined by combining the relationship between thermal stress and crew performance expressed in Tables 2 and 3 into the combined redline limits of Table 5. In addition to rectal or core temperature limits, Table 5 also relates the more frequently utilized heat storage limits to human

performance decrements. A heat storage level of 300-400 Btus, for example, or a rectal temperature of 37.7-38.2 degrees C, is now expressed as a redline equivalent to the first observed decrement in cognitive tasks or manual dexterity (called the Decreased Manual Dexterity or Cognitive Deficit Onset line (DMD or CDO). Likewise, as heat storage and core temperature increase to more serious levels of risk and possible heat exhaustion, 400-600 Btu, or 38.2-39.2 degrees C, are now manifested as a Loss of Tracking Skills (or LOTS line). Superposing these DMD, CDO or LOTS redlines against the results of Figure 6 or similar figures, transform the Wissler and 41 Node Man models from heat storage or rectal temperature simulators to forecasters of performance decrement, a tool more easily appreciated as an index of risk.

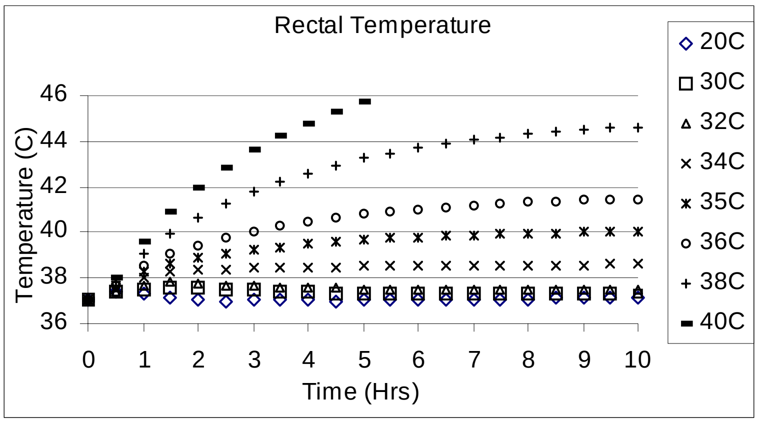

Figure 4 Rectal Temperatures as Function of Time for Parametric Cabin Temperatures; Metabolic Rate is 151 kcal/h (600 BTU h^{-1})

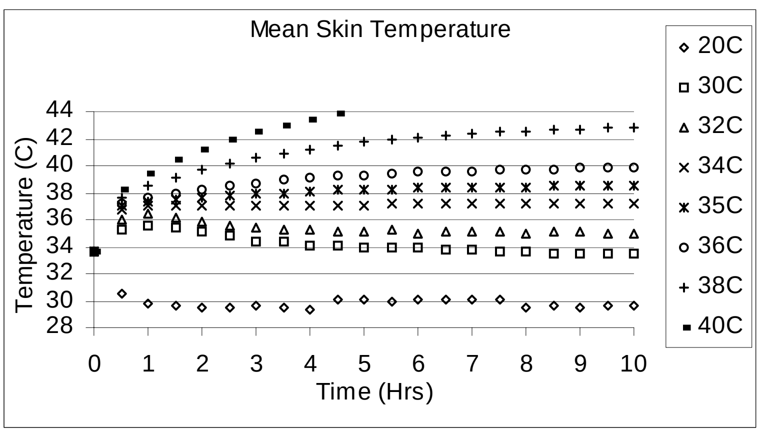

Figure 5 Mean Skin Temperatures for Parametric Cabin Temperatures; Metabolic Rate is 151 kcal/h (600 BTU h^{-1})

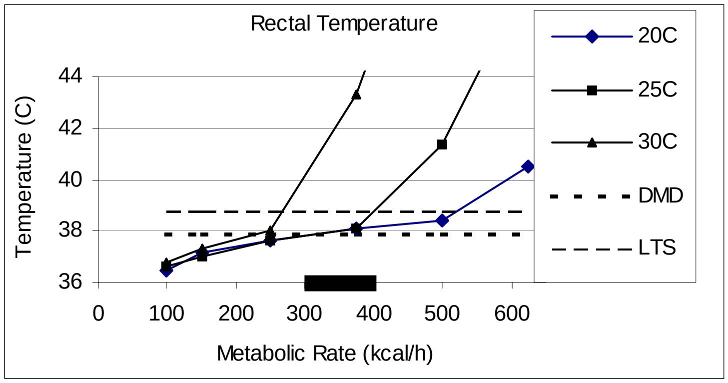

Figure 6 Steady-State Rectal Temperatures vs Metabolic Rate for Parametric Cabin Temperatures
DMD = Decreasing Manual Dexterity (37.9°C) (3)
LOTS = Loss of Tracking Skills (38.8°C) (3)
Upper Limit of Interest
LCVG Upper Steady-State Design Limit = 403 kcal h^{-1}

RECTAL TEMPERATURE LIMITS, °C	EQUIVALENT HEAT STORAGE BTU	MEDICAL CONDITIONS
37.7–38.2	300–400	Cognitive Tasks Decrement onset Decreasing manual dexterity Discomfort (NIOSH limit) Hyperthermia/Heat Stress
38.2–39.2	400-600	Slowed cognitive function Increased errors in judgment Loss of tracking skills 25% risk of heat casualties Possible Heat Exhaustion
39.2–39.6	600-800	Functional limit of physical tasks 50% risk of heat casualties Probable Heat Exhaustion Possible Heat Stroke
>40	> 800	100% risk of heat casualties Probable heat stroke

Table 5 Human Thermal Regulatory Limits

By way of example, the results of Figure 6, combined with Table 5 illustrate that these DMD and CDO limits are approached at a 25 degree C cabin temperature as metabolic rates rise above 200 kcal h^{-1} (600 BTU h^{-1}). Similar simulations performed with the 41 Node Man model show that the LCVG as presently configured is wholly inadequate at cabin temperatures above 35 degrees C. These results and other parametric studies were used to produce Table 6 (11), an estimate of the Cognitive Deficit Onset (CDO) and Loss of Tracking Skills (LOTS) limits for a range of hot cabin reentry scenarios. Table 6 was eventually embodied in the form of formal NASA flight rule (A13-151, Hot Cabin Atmosphere) for the hot cabin reentry scenario.

	Temperature				
	70 °F 21.1 °C	80 °F 26.7 °C	90 °F 32.2 °C	95 °F 35.0 °C	100 °F 37.8 °C
Time to CDO with ACES off	>> 3 h	>> 3 h	3.25 h	2.45 h extrapolated	1.66 h
Time to CDO with ACES on	>> 3 h	>> 3 h	1.25 h	0.75 h extrapolated	0.25 h
Max Metabolic rate to remain below LOTS with ACES on	~2000 BTU h^{-1} (13 min mile)	~1400 BTU h^{-1} (fighter pilot)	~825 BTU h^{-1} (suit donning assisted)	~550 BTU h^{-1} (quiet sitting)	~400 BTU h^{-1} (at rest)

CDO = Cognitive Decrement Onset , 99.9 – 100.9 °F
LOTS = Loss of Tracking Skills, 100.8–102.6 °F

Table 6 NASA Flight Rules A13-151 Hot Cabin Atmosphere, from (11)

CONCLUSIONS

Thermoregulatory models, such as the Wissler and 41 Node Metabolic Man models, are versatile tools that can determine the heat distribution and risk for an individual under a variety of conditions, including astronauts wearing the ACES and LCVG. For the Shuttle, if the cabin temperature rises above 25°C and the metabolic rate increases above 200 kcal h^{-1} (600 BTU h^{-1}) the critical performance parameters of rectal temperature and stored heat approach the DMD and CDO limits. At the upper limit metabolic rates of 300-400 kcal h^{-1} (1200-1600 BTH h^{-1}) the LCVG as configured is predicted to be inadequate. Subsequent studies (in press) have shown that the robustness of the system can be greatly improved by providing lower LCVG inlet coolant temperatures. This would result in an increased margin against incurring performance impairments. The conclusions of this study were instrumental in changing an existing NASA Flight Rule (A13-151) that had required wearing the ACES in a hot cabin reentry with a failed flash evaporator or cabin fan. The revised flight rule, based on this analysis, requires the ACES to be removed and the crew to be in shirtsleeves if the cabin temperature exceeds 35 °C (95 °F) prior to reentry.

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NOMENCLATURE

ACES = advanced crew escape suit
ATCS = active thermal control system
BTU = British thermal unit

EMU = extravehicular mobility unit
EVA = extravehicular activity
LCVG = liquid cooling and ventilation garment
STS = Space Transportation System
WCLS = water coolant loop system

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